submitted to Phys. Rev. E

Beam interactions in one-dimensional saturable waveguide arrays

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(Dated: February 2, 2008)

Abstract

The interaction between two parallel beams in one-dimensional discrete saturable systems has been investigated using lithium niobate nonlinear waveguide arrays. When the beams are separated by one channel and in-phase it is possible to observe soliton fusion at low power levels. This new result is confirmed numerically. By increasing the power, soliton-like propagation of weakly-coupled beams occurs. When the beams are out-of-phase the most interesting result is the existence of oscillations which resemble the recently discovered Tamm oscillations.

PACS numbers: 42.82.Et, 42.65.Tg

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I. INTRODUCTION

There is a growing interest in routing, guiding, and manipulating light by light itself. Such an all-optical concept can be accomplished through the interaction of self-guided beams, which are often called spatial solitons [1,2]. These localized structures are found to exist in various settings such as, for example, plasmas [3], Josephson junctions[4], molecular chains [5], and in nonlinear optics [6]. In the latter case, the refractive index profile induced by a soliton beam exactly balances the inherent beam divergence due to diffraction. It has been demonstrated that logic gates and all-optical switching are possible exploiting the interaction of a couple of parallel beams [7-9]. Here the mutual interaction of two beams, resulting from the additional contribution to the induced refractive index change of the overlapping input fields, depends crucially on their relative phase. When the beams are in-phase they attract each other while repulsion occurs if they are π out of phase [10-12]. In intermediate cases there appears an energy transfer between the two beams [9,13].

Homogeneous nonlinear waveguide arrays (NWA) represent a periodic arrangement of parallel, weakly coupled waveguides. They have been realized in semiconductors [14], photorefractive crystals [15-17], and nematic liquid crystals [18], to mention a few. NWA could be, for example, used for switching [19], passive mode locking [20], and tapered laser arrays [21]. Interactions of two initially parallel beams have been, up to date, investigated only in AlGaAs waveguide arrays exhibiting a cubic, self-focusing Kerr-like nonlinearity [22,23]. In this work, we focus on interactions of parallel beams in one-dimensional NWA in lithium niobate. It is well-known that this photovoltaic photorefractive material exhibits a self-defocusing nonlinear response that has a saturable nature [24]. Our main findings are the demonstration of fusion of two in-phase beams and oscillations in the case of out-of-phase beams. We demonstrate numerically that these effects exist in cubic self-defocusing discrete media, too.

The paper is organized as follows. In Sec. II we describe our experimental setup. Sec. III is devoted to the interactions of in-phase beams. Here, we present our experimental results which have been confirmed numerically by simulations based on a nonlinear beam propagation method. For the sake of completeness, we add the corresponding numerical results for cubic self-defocusing media. In Sec. IV we analyze numerically the interactions of out-of-phase beams in both saturable and cubic NWA while the conclusions are given in

Sec. V.

II. EXPERIMENTAL METHODS

Our sample is a 27 mm long, x-cut lithium niobate crystal. Permanent channel waveguides are fabricated by Ti indiffusion. A lithographically patterned Ti layer with a thickness of 10 nm is annealed for 2 hours at a temperature $T = 1040\,^{\circ}$C. The sample is thereafter surface doped by Fe (5.6 nm Fe layer, annealed for 24 hours at $T = 1060\,^{\circ}$C). This additional doping serves to enhance the photorefractive effect. Each channel is $4\,\mu$m wide and forms a single-mode waveguide for TE polarized green light. The distance between adjacent channels is $4.4\,\mu$m, which results in a lattice period of $\Lambda = 8.4\,\mu$m. The input and output facet of the sample are finally polished to optical quality.

Our experimental setup is sketched in Fig. 1. The light source is a Nd:YVO_4 laser that provides single-frequency output at a wavelength $\lambda = 532\,$nm. We form a 3 cm wide quasi-plane wave by means of a beam expander (20× microscope lens and collimation by a second lens with focal length $f = 200\,$mm). To excite different light patterns on the input face of the sample, an adequate amplitude mask (titanium on glass substrate covered by photo resist) has been fabricated using a laser beam writer. The mask is placed in front of a 40× microscope lens that images two illuminated holes of the mask with a diameter of $2r = 142\,\mu$m separated by $d = 704\,\mu$m. This mask transmits two in-phase beams which are adjusted by virtue of the microscope lens in such a way to excite only two channels of the array. As the coupling in our NWA is relatively weak we restrict our study to the case in which these two channels are separated by one channel. Green light from the output facet is collected by another 20× microscope lens and imaged onto a CCD camera.

III. INTERACTIONS OF IN-PHASE BEAMS

As is well established, scalar wave propagation in a nonlinear one-dimensional WA can be modelled within a paraxial approximation by:

$$i\frac{\partial E}{\partial y} + \frac{1}{2k}\frac{\partial^2 E}{\partial z^2} + k\frac{n(z) + \Delta n_{nl}}{n_s}E = 0\ . \qquad (1)$$

The propagation coordinate is along the y-axis, the amplitude of the electrical field is denoted by E, while $k = 2\pi n_s/\lambda$ represents the wave number. Here, λ is the wavelength of the used

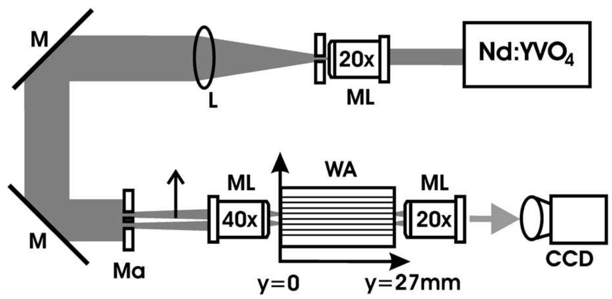

FIG. 1: Experimental setup: ML, microscope lens; L, lens; M, dielectric mirrors; Ma, mask; WA, waveguide array; CCD, CCD camera.

light in vacuum while $n_s = 2.2341$ is the extraordinary refractive index of our lithium niobate substrate. The periodically modulated refractive index which defines the nonlinear WA is denoted by $n(z)$ while Δn_{nl} is the nonlinear refractive index change ($\Delta n_{nl} << n_s$). The periodically modulated refractive index can be well approximated by $n(z) = 2.2341 + 0.01035\cos^2(\pi z/\Lambda)$.

In the following we investigate the interaction of two in-phase beams separated by one channel on the input facet. In Fig. 2 we give typical examples of experimentally observed discrete diffraction and nonlinear interaction of the two beams, respectively. Here each of the beams has an optical power $P \approx 7\,\mu$W. An image of discrete diffraction of two beams from the output facet of the lithium niobate NWA is presented in Fig. 2a. In parts b) and c) the corresponding images of discrete diffraction when one of the beams is blocked are presented. These light distributions serve us to ensure the correct input excitation with straight propagation within the array (zero transverse wave vector component). In Fig. 2d we monitor the temporal evolution of the interaction of the two beams. After an initial stage of discrete diffraction and a short transient regime a stable, steady state, two-hump structure is formed within a few minutes.

In Fig. 3 we present experimental results for different power levels of the two parallel beams and compare the obtained results with numerical modelling. For this we solve Eq. (1) numerically by using a nonlinear beam propagation method (BPM). We used the parameters of our WA and a saturable defocusing nonlinearity of the form

$$\Delta n_{nl} = \Delta n_0 I/(I + I_d) \ , \qquad (2)$$

with amplitude $|\Delta n_0| = 3 \times 10^{-4}$ and an intensity ratio $r = I/I_d$, where I_d is the so-called

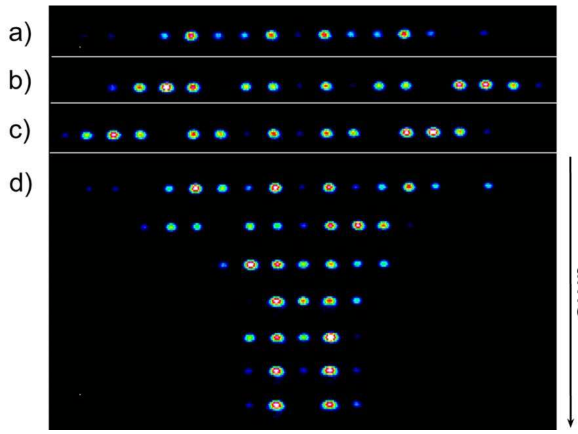

FIG. 2: (Color online) Discrete diffraction (a-c) and nonlinear interaction (d) of two co-propagating in-phase beams. The photographs show the corresponding images on the output facet of the NWA when: a) both beams are present; b, c) one beam is blocked, and d) time evolution of two-beam interaction for an input power of $P \approx 7\,\mu$W.

dark irradiance and I is the light peak intensity.

In Fig. 3 a) linear discrete diffraction is measured and compared with theory, yielding the corresponding coupling constant of $L_c = 3.4\,$mm of our sample. Experimentally, in the low power regime ($P \approx 0.5\,\mu$W) in b) we observe soliton fusion in the central channel of the array, in good agreement with the BPM results. This process is absent in the cubic case [23]. On the other hand, soliton fusion has been observed in both bulk and planar waveguide photorefractive crystals exhibiting a saturable nonlinearity [25,26]. The formed structure possess a highly symmetric form of strongly localized mode A [27,28]. In the regime of mediate power in c) it is possible to obtain almost independent, soliton-like propagation of the two beams, as observed for single-channel excitation [28]. Here one can observe weak oscillations which result in light localization either in the central element or in its first neighbors, which can be understood by the remaining weak evanescent coupling of the two parallel waveguides. This oscillatory behavior has been reported in Ref. 23, too. For higher power and thus a stronger effect of saturation we observe a widening of the formed structure (Fig. 3d), again in good agreement with numerics.

It is well known that photorefractive crystals such as strontium barium niobate and lithium niobate have a non-instantaneous nonlinear response [29]. Depending on light intensities, build-up times in these materials range from a few milliseconds to a few minutes or

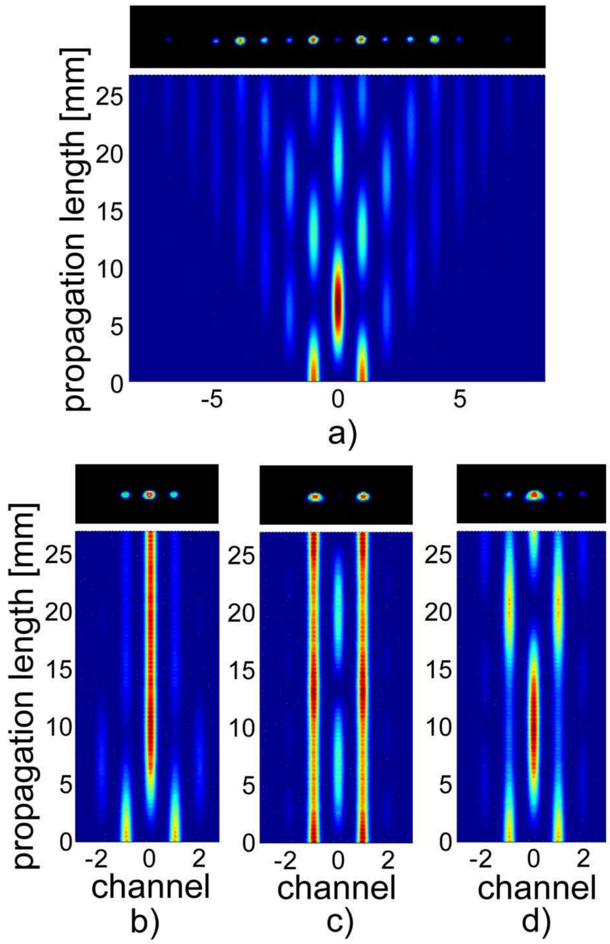

FIG. 3: (Color online) (Color online) Comparison of in-phase interaction for different input powers and saturable nonlinearity. a) Discrete diffraction. b) Soliton fusion: $P \approx 0.5\,\mu$W, $r = 0.43$. c) Soliton-like propagation: $P \approx 7\,\mu$W, $r = 4.62$. d) A wide structure: $P \approx 25\,\mu$W, $r = 30$.

even hours. Thus, we are able to perform a specific read-out of the light induced structures that have been presented in Figs. 2 and 3. For this, after recording of stationary refractive index changes we block one of two writing beams. The residual beam is still able to "see" the former light-induced refractive index change, as demonstrated in Fig. 4: The two induced waveguides are evanescently coupled to each other, leading to partial energy transfer from one channel to the other.

The fact that the output from the array can be controlled by changing only the power of two beams may be attractive for fast all-optical gating. Therefore, we perform simulations in WA with instantaneous cubic nonlinearity [2,11,22,23]. In this case we have $\Delta n_{nl} = \Delta n_0 I$. We arbitrarily take, as before, $|\Delta n_0| = 3 \times 10^{-4}$ and the above mentioned data for our

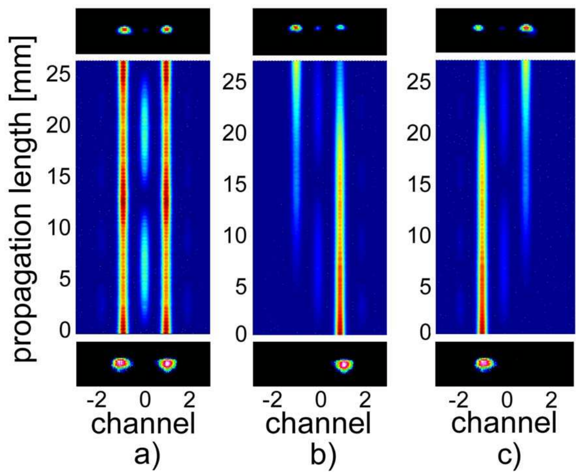

FIG. 4: (Color online) Read-out of light-induced structures. Upper parts: images from the input facet (top) and the corresponding images from the output facet (bottom). Lower parts: numerical simulation of build-up (a) and single beam propagation (b,c) in the induced structure. a) Initial two-beam interaction; b) and c) read-out of the induced structure with a probe beam coupled in the left or right input channel, respectively.

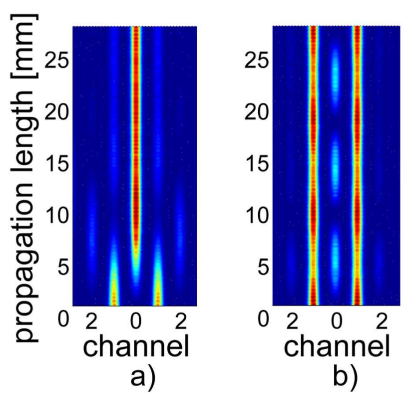

FIG. 5: (Color online) Interaction of in-phase beams for cubic nonlinearity: a) Fusion of two beams with $\Delta n_{nl} = 2.8 \times 10^{-5}$. b) Nearly independent propagation of two soliton-like beams for $\Delta n_{nl} = 6.2 \times 10^{-5}$.

waveguide array. Most important results shown in Fig. 5 [the fusion of solitons in a) and the soliton-like propagation of two beams in b)] reveal that the interaction of two parallel in-phase beams is independent of the type of nonlinearity.

IV. INTERACTIONS OF OUT-OF-PHASE BEAMS

In this Section we study numerically interactions of two out-of-phase beams in a WA for both saturable and cubic defocusing nonlinearities. From the investigation of bulk and waveguide arrays with cubic nonlinearity, it is known that out-of-phase parallel beams will repel each other [10-12,23].

Some examples of our numerical results are shown in Fig. 6. The first four pictures are devoted to the saturable case while the last two are for a cubic (Kerr) nonlinearity. In the low power regime (a) one can recognize the expected repulsive behavior of this interaction while in the high power regime (d, f) we find a practically independent propagation of two soliton beams. These results are in full agreement with the corresponding findings from self-focusing discrete media with cubic nonlinearity [23]. However, the oscillations presented in (b, c, e) that are observed for mediate power levels are a completely new phenomenon which resembles the recently observed Tamm oscillations at the interface between a homogeneous substrate and a WA [30]. An intuitive explanation is that out-of-phase beams are reflected back from the specific channel for which the Bragg condition is fulfilled. Bloch oscillations [31] occur as a special case of Tamm oscillations when the repulsive potential is a linear function of the distance from the edge of the array. These oscillations have a promising role in all-optical switching at low power level as reported, for example, in Ref. 32. Here it is important to mention that in this Section we use the corresponding data of another sample which has an approximately three times shorter coupling length of $L_c = 1.1\,\mathrm{mm}$ [33]. Namely, as has been shown in Ref. 30, the period of Tamm oscillations increases with the growth of the coupling length. Thus, our 27 mm long iron-doped sample is still too short to observe a clear oscillatory behavior. Also, the corresponding data for Δn_{nl} used for the saturable case are around the maximally achievable value of nonlinear refractive index changes in lithium niobate, which is of the order of 1×10^{-3}. For lower values of Δn_{nl} it remains difficult to observe both multiple oscillations and soliton-like propagation of two beams.

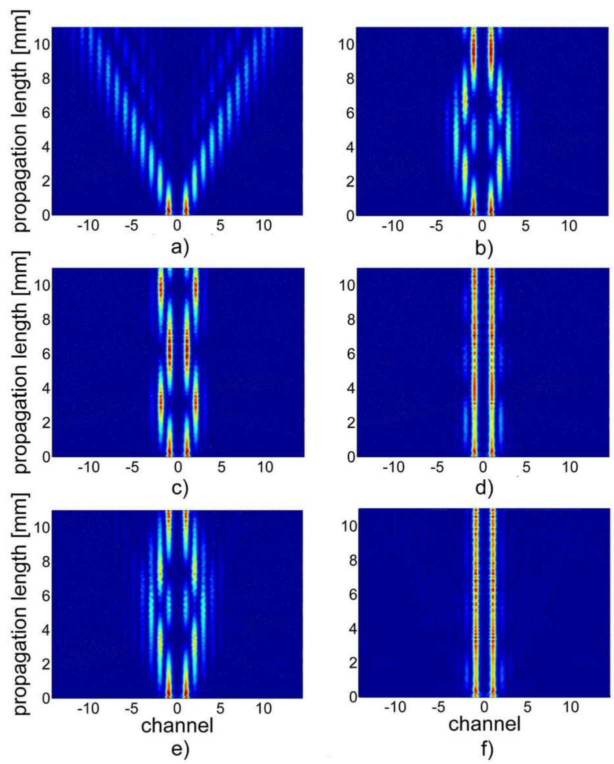

FIG. 6: (Color online) Interaction of two out-of-phase beams in saturable self-defocusing media (a-d) and cubic self-defocusing media (e,f): a) repulsion for $\Delta n_{nl} = 9 \times 10^{-4}$ and $r = 0.6$; b) one oscillation for $\Delta n_{nl} = 9 \times 10^{-4}$ and $r = 2.61$; c) two oscillations for $\Delta n_{nl} = 9 \times 10^{-4}$ and $r = 5$; d) undisturbed propagation of two soliton-like beams for $\Delta n_{nl} = 1.15 \times 10^{-3}$ and $r = 5$; e) one oscillation for $\Delta n_{nl} = 3.65 \times 10^{-4}$; and f) two soliton-like beams for $\Delta n_{nl} = 5 \times 10^{-4}$.

V. CONCLUSION

The interaction between two parallel beams in one-dimensional nonlinear waveguide arrays is investigated both experimentally and numerically. As our iron-doped lithium niobate sample has rather low coupling constant we concentrate on the case in which these beams are separated by a single channel. We observe a complete fusion of two in-phase beams at low power level. For higher input power the interaction decreases and nearly independent propagation of two separated solitons is observed. Another phenomenon which does not have an analog in the self-focusing domain is the oscillatory behavior of two out-of-phase beams. Both effects are also obtained numerically in waveguide arrays exhibiting an instantaneous cubic nonlinearity. Finally, our findings are of considerable interest for all-optical

gating and switching using discrete soliton interaction in waveguide arrays.

Acknowledgments

This work has been supported by the German Federal Ministry of Education and Research (BMBF, grant DIP-E6.1) and the German Research Foundation (DFG, grant KI482/8-1)).

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